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Annual Progress Report

"Interpretation of *Voyager* UVS Observations of Occultations by the Atmopshere of Neptune"

NASA Grant NAGW-2441

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A Proposal to Continue the Program

Interpretation of Voyager UVS Observations of Occultations by the Atmosphere of Neptune

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For the Second of Three Years

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1.0 Introduction

We propose to continue our investigation of the upper atmosphere of Neptune based primarily on the solar occultation measurements made by the Voyager UVS. The ultimate goal of this research is to understand the structure and composition of Neptune's upper atmosphere as encoded in the data base obtained by the UVS during the Voyager 2 encounter with Neptune. The UVS occultations provide information essential to studies of atmospheric composition and structure, energy balance, photochemistry, global transport, ionospheric structure, and airglow production mechanisms. In conjunction with other research in progress at the University of Arizona and by our colleagues at other institutions, we not only analyze and interpret individual measurements or observations by the UVS, but also construct models of the upper atmosphere which are consistent with all available data obtained by the UVS. We derive constraints from measurements of the atmospheric emissions and we combine these with constraints derived from the occultation measurements. Principal sources for the atmospheric emissions include dayglow, resonance scattering and, at long wavelengths, the reflected solar spectrum. On the dark side of the planet, a weak H Ly α emission is due to resonance scattering of the sky background and perhaps another source. Thus a wide range of physical processes are at work, and each provides its own constraints on the atmosphere.

Some of the research supported by this proposal benefits our understanding of occultations by bodies other than Neptune, so to take full advantage of them we have not confined our attention to Neptune. This is especially appropriate in view of the fact that Voyager has now visited four of the outer planets, two of which have satellites that possess substantial atmospheres, and so offers opportunities for comparative studies on an unprecedented scale. Also we have supported investigations of the atmosphere of Triton using the solar occultations by that body.

2.0 Progress

The following sections summarize recent work, most of which has been published or prepared for presentation at meetings of the Division of Planetary Sciences of the AAS or the Neptune and Triton conference soon to be held at the University of Arizona. In addition to this work, we are preparing a chapter for the Neptune and Triton book (Bishop et al., 199?)

2.1 Solar Occultation Analysis Procedures

We have reanalyzed data from the solar occultations by Neptune and Triton. This included the first detailed analysis of the Neptune exit occultation. Much of the effort centered on finalizing the procedure for correcting the effects of the motions of the Sun in the field of view that were caused by limit cycle motions of the spacecraft.

For the Triton occultations, we have detected and corrected a drift of the true position of the Sun in the field relative to the position inferred from Voyager engineering telemetry by comparing the occultation data with sun calibration observations. We have corrected a slight variation in response with position of the Sun along the length of the UVS slit, by using reference (unattenuated) spectra taken after the period of atmospheric absorption in the Neptune exit occultation to determine the variation.

The unattenuated portion of the Neptune exit occultation observation did not fully sample the variation of sensitivity with position across the width of the slit. Thus comparison of part of the occultation spectra with unattenuated spectra taken immediately afterward was impossible. To overcome this difficulty, we have developed a technique that permits us to use Triton reference spectra for the analysis of the Neptune exit occultation. (This procedure relies on a different set of spectra than the procedure described in the preceding paragraph, so that circularity is avoided.)

Other improvements in analysis techniques have included the development of a procedure for smoothing reference spectra in position across the slit, an adjustment in the second-order contribution of the descattering matrix, and a verification of our algorithm that linearizes the response of the UVS detector.

Much of this analysis has been done by R. J. Vervack, Jr., a graduate student in the Department of Planetary Sciences at the University of Arizona.

2.2 Thermal Structure of Neptune's Upper Atmosphere

We have used data from the solar occultation to constrain the temperature profile of Neptune's upper atmosphere. Based on the absorption characteristics of the atmosphere at wavelengths below 850 Å, where ionization of molecular hydrogen is the dominant extinction process, we have made a preliminary determination of the temperature in the upper thermosphere. The exit occultation, which occurred at a latitude of 49° S, yields a temperature near 500 K at and altitude of about 2000 km above 1 bar, where the pressure is about 10^{-5} μbar. The entrance occultation, which occurred at a latitude of 61° N, yields a temperature lower than originally estimated. Wavelengths longer than 1550 Å probe the upper stratosphere. Rayleigh-Raman scattering by molecular hydrogen is the dominant extinction process at these wavelengths. Analysis of the exit occultation data yields a temperature of 160 K at an altitude of 225 km where the pressure is 240 μbar. Corresponding values for the entrance occultation are 120 to 130 K at 210 km and a pressure of 220 μbar. (These results will be presented at the Neptune and Triton conference by Yelle et al. (1992)).

2.3 Hydrocarbons in Neptune's Stratosphere

We have developed new objective techniques involving the analysis of variance (Herbert and Sandel, 1991) to study occultation data, and have used them to infer hydrocarbon abundances in Neptune's stratosphere. The resulting profiles of H_2, CH_4, and C_2H_6 appear to be well defined within a scale height of 260, 600, and 400 km, respectively (relative to the 1-bar level as defined by Tyler et al., 1989) at both entrance and exit sites. The mixing ratios $[CH_4]/[H_2]$ and $[C_2H_6]/[H_2]$ are roughly 10^{-4} and 10^{-5} at 550 and 400 km, respectively.

The detection ranges of CH_4 and C_2H_6 nearly coincide at about 500 km, and there $[C_2H_6]/[CH_4] \sim 0.01$. An upper limit was found for C_2H_2 ($[C_2H_2]/[CH_4] <$ 0.005), while C_2H_4 may have been marginally detected ($[C_2H_4]/[C_2H_6] \sim 0.01$, or this may be an upper limit). The scale height of CH_4 decreases rapidly above 550 km, indicating the proximity of the homopause. H_2 and hydrocarbon profiles as determined by this technique are shown in Figure 1.

Neptune's stratospheric CH_4 is detectable at atmospheric pressures as low a roughly 0.1 μbar, as it was at Saturn, whereas at Uranus CH_4 was difficult to detect at 10 μbar (order of magnitude pressure estimates). Therefore, in this respect Neptune's stratosphere resembles Saturn's more than Uranus's. The implication is that Uranus is the unique object, with orders of magnitude less stratospheric mixing than Saturn or Neptune, suggesting the importance of an internal planetary heat source for stirring the atmospheres of the giant planets. (Herbert et al., 1992)

The technique described above represents a data-driven approach to inferring observable quantities from the occultation measurements. Another approach, based on comparing the results of photochemical models with the data, may also be fruitful. We have supported the comparison of occultation lightcurves in the 1250-1380 Å wavelength range with one-dimensional methane photochemical-transport models. Photoabsorption by methane (the photochemical parent) is expected to be the major

Neptune Hydrocarbon Profiles

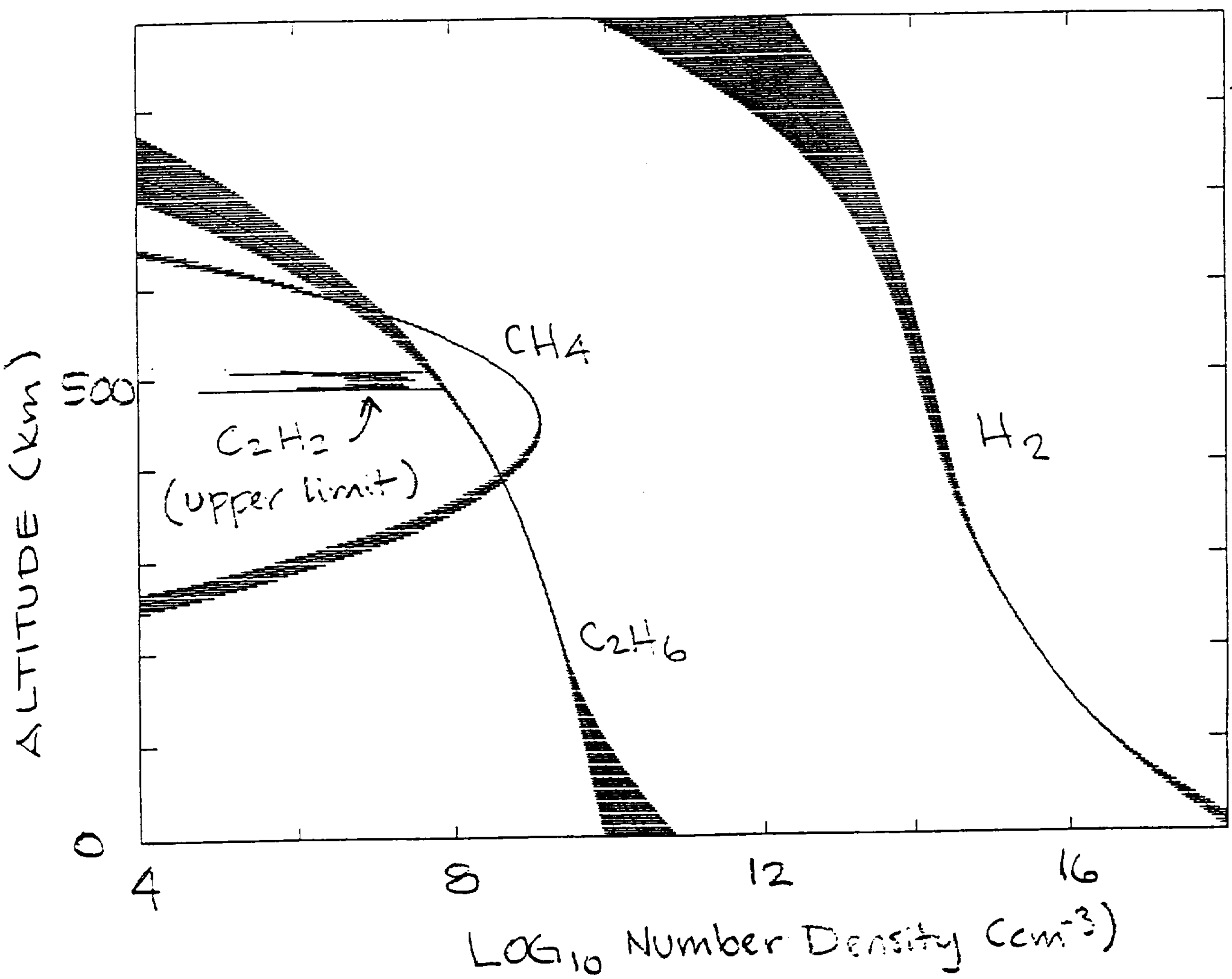

FIGURE 1

source of opacity at these wavelengths, in which case the lightcurves can be used to infer the strength of eddy mixing at altitudes above the methane photolysis peak and compatible methane mixing ratios in the lower stratosphere. For the p-T models adopted in this study, acceptable fits to the lightcurves are obtained with model values of the eddy mixing coefficient ($K_{1/2}$) near the half-light altitudes of $2\text{-}15\times10^6$ cm^2 sec^{-1} (ingress) and $4\text{-}35\times10^6$ cm^2 sec^{-1} (egress). These models imply lower stratospheric ($p > 1.0$ mbar) methane mixing ratio values ($f(CH_4)$) of $5\text{-}100\times10^{-5}$ (ingress and egress). The ranges in the model values $f(CH_4)$ and $K_{1/2}$ reflect uncertainties in the background p-T structure and different criteria for choosing a "good fit." For the nominal p-T models and a criterion based on replicating the spacing in altitude of the 1250-1380 Å lightcurves, $K_{1/2}$ values of 10^7 cm^2 sec^{-1} (ingress) and $1\text{-}2\times10^7$cm^2 sec^{-1} (egress) and $f(CH_4)$ values of $\sim1\times10^{-4}$ (ingress and egress) are indicated, with the egress results being more uncertain. These results are insensitive to photochemical details of the models. (Bishop et al, 1991.)

2.4 Haze in Triton's Atmosphere

Herbert and Sandel (1991) have analyzed the solar occultation by Triton, finding two constituents of the troposphere: CH_4 and another absorber visible between 1400 and 1600 Å below about 20 km altitude. The CH_4 appears to be saturated at the surface at both entrance and exit occultation sites. The density scale height and wavelength dependence of the long-wavelength absorber are consistent with Rayleigh scattering of N_2. However, the inferred N_2 column abundance is inconsistent with the Voyager radio science (RSS) occultation measurement, and so the N_2 hypothesis is discarded. An alternative hypothesis for the identity of the long-wavelength opacity that was studied by Herbert and Sandel (1991) is Rayleigh scattering by an aerosol haze, because the optical depth is noticeably wavelength dependent, both within the range of measurement of the UVS and over the range between the FUV and visual wavelengths. FUV Rayleigh scattering requires that the haze particles be very small (<0.03 μm) and abundant. These characteristics suggest formation as photochemical smog or condensing N_2 with a great abundance of nucleation centers. Condensation onto ions allows rapid formation of very small particles, so possibly ions created by penetrating charged particles (0.1 to several MeV) are nucleating the haze. Small particle size also promotes long residence times against settling, essential for accumulation to significant abundance and suggesting that eddy transport dominates settling. If this is the case, the haze scale height likely approximates the gas scale height and the implied temperature is around 38 K. This is lower than the 50 K estimated by RSS, and is also too low for the dust devil hypothesis for the visible atmospheric plumes.

More recently, Krasnopolsky et al. (1991) have taken a somewhat different approach by modelling the formation of haze by methane photolysis products. This approach attributes the long-wavelength opacity to absorption rather than to Rayleigh scattering. The modelling requires knowledge of the methane altitude profile and optical data at two wavelengths to determine the two free parameters: cross section weighted-mean radius r_c and particle material density ρ. Using Voyager UVS measurements of CH_4 and haze combined with the haze brightness profile determined by the narrow angle camera, they infer haze optical thickness of 0.024 at 1500 Å and 7.8×10^{-3} in the spectral range of the narrow angle camera centered at 4700 Å, $\rho/\gamma = 0.36 \pm 0.1$ g/cm^3 (γ is the quantum yield of condensate), and values of r_c varying from 0.1 ± 0.02 μm at 30 km to 0.15 ± 0.03 μm near the surface. Other auxilliary properties of the haze are also determined. The value found for ρ/γ corresponds to a packing coefficient of 0.6γ if C_2H_4 is the main condensible species. (Krasnopolsky et al., 1991)

2.5 *Hydrocarbons in Saturn's Atmosphere*

The Voyager UVS experiment measured the ultraviolet absorption properties of Saturn's upper atmosphere by observing the occultation of the star δ Scorpii. Saturn's atmosphere is of particular interest because of its similarity in certain respects to that of Neptune, as mentioned earlier. Important absorbers in the UV from 1300 to 1700 Å include CH_4, C_2H_2, C_2H_4, C_2H_6, and C_4H_2. We have inferred number density distributions for these hydrocarbons by inverting the occultation light curves with a linear constrained matrix technique. The inversion method is an extension of the techniques developed by Twomey. By carefully choosing the wavelength intervals used in the analysis and applying some reasonable physical constraints, we determined the number density of CH_4 from 800 to 1030 km, C_2H_2, C_2H_4, and C_2H_6 from 630 to 1030 km and C_4H_2 from 730 to 1030 km. The analysis implies surprisingly high densities of C_2H_6 relative to CH_4, in conflict with expectations from photochemical models (Feng et al., 1991).

3.0 Continuing Research

In the next two years we plan to continue generally along the lines already established this year. Specific research areas that we expect to pursue are described briefly in the following sections.

3.1 Thermal Structure

3.1.1 Theoretical Approach. The high temperature of the outer planet thermospheres is due to a high-altitude heat source of unknown nature coupled with the inability of the atmosphere to radiate away this heat at any level above the bottom of the stratosphere. Yelle and graduate student Wang are developing theoretical models of the IR radiation efficiency of the stratosphere so that the only remaining unknown left to fit by the occultation data will be the altitude and strength of the high altitude heat source. With fewer unknowns to constrain, their values will be more accurately determined and thus the mechanism of the heat source will be better constrained.

3.1.2 Occultation data analysis. We and collaborators have developed an analysis procedure for analyzing heat inputs in H_2 thermospheres by integrating the heat conduction equation and adjusting the heat sources to produce a temperature and density model that reproduces the occultation light curves [M.H. Stevens, PhD Thesis, Johns Hopkins University, 1991]. This technique has been successfully used to analyze the heat inputs to the Uranian thermosphere and will be applied to Neptune, so as to derive locations and strengths of the heat sources and sinks in the thermosphere.

An alternative approach, involving the detailed construction of a curve-of-growth in a highly inhomogeneous line-of-sight, has been developed by Yelle and graduate student Wentzel. This approach fits a density profile, via its effects on opacity, to the occultation light curves. Following this a thermal model is adjusted to maximally fit the derived density model. This technique will also be used to derive the locations and strengths of the heat sources and sinks of the thermosphere.

3.2 Hydrocarbon Abundances

Herbert and Sandel [1991] introduced singular-value-decomposition inversion to the problem of simultaneously determining the altitude profiles of several atmospheric species. They applied this problem to Triton, where it made possible the determination of the CH_4 profile to lower altitudes than was previously possible. This procedure is now being applied to the hydrocarbon distribution in Neptune's stratosphere [Herbert et al. 1992], as described in 2.3. Further work will refine the error limits and extend the altitude range. This work will be coupled with the photochemical modeling just discussed.

A somewhat different approach has been developed by Feng, Yelle and graduate student Wentzel. This work breaks the occultation light curve analysis into several segments, including the determination of smoothed optical depth profiles, disentangling the superposition of atmospheric layers, and finally a simultaneous fit to the different species. The advantage here is that an independent check on the svd methodology is developed. This work will proceed in cooperation with that just described.

3.3 Solar EUV flux.

We are initiating a collaborative program to investigate the solar EUV flux and its variation over the solar cycle and the 25-day solar rotation period. This program will not be funded under our NDAP program, but we will make expertise and techniques developed for the analysis of the solar occultations available for the solar research. The research will be carried out by Giuliana de Toma of the University of Trieste, Italy. We expect that the results of the solar research will benefit our NDAP program in two ways. First, the study of certain technical details of the functioning of the UVS will lead to better understanding of the occultation data. Second, new information about the absolute value and variations in the solar EUV flux will increase our understanding of the physical processes in the atmospheres of the outer planets.

The Voyager solar observations now span more than one solar cycle, and include two maxima and one minima. Furthermore, the UVS instruments have from time made series of solar observations spaced over the 25-day rotation period. Study of these observations should reveal new information about variations of the solar EUV on the two most important time scales. This research will also include comparison of the observed solar flux and its variations with that predicted by a theoretical model of the solar atmosphere.

4.0 Publications

Research described in the following publications has received support from this grant.

Bishop, J., S.K Atreya, B. R. Sandel, R. V. Yelle, P. N. Romani, and G. S. Orton, The middle and upper atmosphere of Neptune: Vertical structure and the distribution of hydrocarbon species, to be presented at the Neptune and Triton Conference, Tucson, January 1992, and in preparation as a chapter in Neptune and Triton, D. P. Cruikshank, ed., University of Arizona Press, 199?

Bishop, J., S. K. Atreya, P. N. Romani, B. R. Sandel, and F. Herbert, Voyager 2 UVS solar occultations at Neptune: Constraints on the abundance of methane in the stratosphere, submitted to J. Geophys. Res., 1991.

Feng, D., B. Herman, and R. V. Yelle, Hydrocarbon number density profiles in Saturn's upper atmosphere from the Voyager 2 stellar occultation experiment, presented at the meeting of the DPS, Palo Alto, 1991.

Herbert, F., and B. R. Sandel, CH_4 and Haze in Triton's Lower Atmosphere, J. Geophys. Res. 96, 19,241, 1991.

Herbert, F., R. V. Yelle, T. M. Wentzel, B. R. Sandel, and R. J. Vervack, Jr., Hydrocarbon abundances in Neptune's stratosphere, to be presented at the Neptune and Triton Conference, Tucson, January 1992.

Krasnopolsky, V. A., B. R. Sandel, and F. Herbert, Properties of haze in the atmosphere of Triton, submitted to J. Geophys. Res, 1991.

Krasnopolsky, V.A., B. R. Sandel, and F. Herbert, Properties of haze in the atmosphere of Triton, to be presented at the Neptune and Triton Conference, Tucson, January 1992.

Stevens, M. H., D. F. Strobel, and F. Herbert, Inferring heat sources and model atmospheres from Voyager 2 ultraviolet spectrometer occultation data at Uranus, presented at the meeting of the DPS, Palo Alto, 1991.

Yelle, R. V., T. M. Wentzel, B. R. Sandel, R. J. Vervack, Jr., and F. Herbert, UVS constraints on the thermal structure of Neptune's upper atmosphere, to be presented at the Neptune and Triton Conference, Tucson, January 1992.